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Three-Pass Operation of the IR Demo Driver

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Abstract

On July 2nd, 3rd, and August 1st 2001 we duplicated an operational mode first implemented at Bates (the first author thinks) by J. Flanz and P. Sargent [1] – multipass operation of a single-channel recirculator. For fun, on July 3rd, we also ran [2] the FEL at 1.48 kW upstairs, translating to roughly 2.25 kW downstairs (fireworks for the 4th of July…). This note documents and provides an analysis of these activities.

Description

The Bates recirculator normally serves as a linac energy doubler. Flanz and Sergeant did however test the system over a broad range of recirculated beam reinjection phases, running the machine in several states including energy doubling, energy recovery, and an intermediate mode that saw second pass beam coasting through the linac on zero crossing, recirculating a second time, and energy recovering on a third pass through the linac [3].

Provoked by an ongoing discussion with A. Hutton [4], we have performed a similar test using the IR Demo driver. The native mode of this recirculator is to provide energy recovery. On July 2nd & 3rd 2001 we therefore tested, using specific orbit diagnostic optics (most recently characterized by allsave 673), a range of reinjection phases from the nominal energy recovery to full acceleration (at a recirculator path length ½ RF wavelength shorter than nominal), back to energy recovery (at a recirculator path length a full RF wavelength shorter than nominal). At the intermediate quarter-wavelength offsets, two beams could be seen in the recirculator and some indications of three beams were visible at the end of the cryomodule (allsave 672). After analysis of observations made during these tests, methods for improving beam quality during three-beam operation were developed. When applied on August 1st 2001 (yielding all-save 693), these methods provided adequate beam quality to produce two clearly defined spots at many points within the recirculator, three visible beams at the end of the linac, and a visible spot in the energy recovery dump (at 10 MeV).

Observations on July 2nd and 3rd, 2001

On July 2nd 2001, as an aside to difference orbit characterization of allsave 673, we duplicated a test first performed by Flanz and Sargent [5]. This test was performed at approximately 37 MeV, with beam initially accelerated on crest and energy recovering (to appear in the 1G dump line) at a path length determined by MDG3F02H corrector excitations of ~2000 g-cm. Noting that the path length differential δl generated by a field integral change ΔBL in the DG correctors adjacent to the π-bends (of radius $\rho = 1$ m) is

$$\delta l = 2 \times 2\rho \times \Delta BL/B\rho = 4 \text{ m} \times \Delta BL/B\rho ,$$

we see that the field integral change required to generate a one-RF-period long shift in recirculated beam arrival time at 37 MeV is

$$\Delta BL = (0.2 \text{ m} / 4 \text{ m}) \times 33.3564 \text{ kg-m/(GeV/c)} \times 0.037 \text{ GeV/c} = 6200 \text{ g-cm} .$$

This provides a calibration on the path length; given that the system energy recovers at a DG3F02H excitation of +2000 g-cm, we would expect it to energy recover again at around –4000 g-cm excitation. This in fact was observed; beam was acquired on at least one viewer in the 10 MeV (1G) dump line for each of the extreme phases. Further, two beams were clearly visible at the end of the module (on viewer ITV1F02) for *all* phases from that specified by the nominal path length (at $Bl_{DG3F02H}$ = 2000 g-cm) to that specified by a path length that is a full wavelength shorter ($Bl_{DG3F02H}$ ~ -4000 g-cm). The second-pass output energy of the linac varied from the usual energy-recovered 10 MeV (at the initial phase), up to the nominal operating energy of 37 MeV (at a quarter-wavelength shorter phase, on the module zero-crossing), to as high as ~64 MeV (at a path length a half-wavelength shorter than the energy recovery value). Table 1 provides these and various other associated values; the variation is of course sinusoidal, and, as noted, two beams were clearly visible at the end of the module over the full path length/phase range. This exercise thus energy recovered at two phases, energy doubled, and put coasting beam through the linac at two RF zero crossings (quarter-wavelength points).

Table 1: Phase, path length corrector excitation, and second pass beam energy

Path Length		$Bl_{DG3F02H}$	2nd Pass Beam Energy
Nominal:	mod($\lambda_{RF}/2$)	~ 2000 g-cm	10 MeV
	mod($\lambda_{RF}/4$)	~500 g-cm	37 MeV
Nominal-$\lambda_{RF}/2$:	mod(λ_{RF})	~ -1000 g-cm	64 MeV
	mod($3\lambda_{RF}/4$)	~ -2500 g-cm	37 MeV
Nominal-λ_{RF}:	mod($\lambda_{RF}/2$)	~ -4000 g-cm	10 MeV

At a quarter wavelength below the nominal phase, two beams could be seen on many recirculator viewers and a third pass beam could be seen, albeit faintly, at the end of the module. The second pass beam momentum spread was quite "bad", inasmuch as the beam filled ~80% of the ITV2F06 viewer. This viewer is ~33 mm wide; the beam width was thus ~26 mm at a point with ~0.4 m of dispersion, implying the second pass momentum spread was of order 6.5%. The large momentum spread was a clear impediment to the recirculation and energy recovery of the second pass.

At three-quarters of a wavelength below the nominal phase, two beams could be seen at many recirculator viewers, but there were no visible indications of third pass beam at the end of the module. The apparent momentum spread in the recirculator was similar to that in the previous case. Given the difference in the slope of the RF overvoltage imposed on the coasting beam in each case (Figure 1) and that fact that the recirculator momentum compaction was not adjusted from its nominal value (~ –0.1 m from linac back to linac) in either case, it is perhaps possible that in the first case some energy compression occurred during energy recovery (yielding marginal beam definition at the end of the module) while no compression (or even antidamping of the momentum spread) occurred in the other case, dispersing the already degraded beam. This reasoning provides some hint as to how second and third pass beam quality can be improved – a topic to which we now turn our attention.

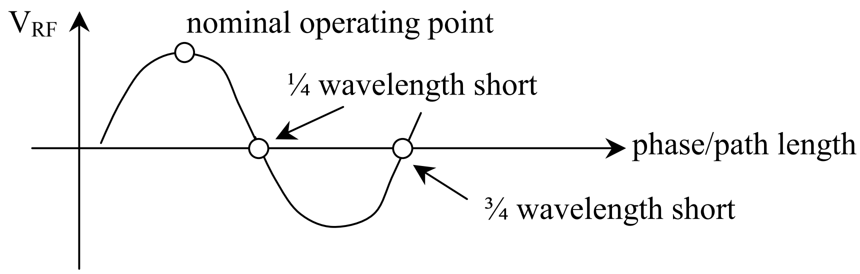

Figure 1: RF Voltage vs. phase at various operating points

Analysis, Simulations & a "Fix"

The source of the large momentum spread during three-pass operation is clear – it is the large overvoltage imposed on the second pass (coasting) beam by the module. In difference orbit diagnostic mode, the first pass beam is accelerated on crest, generating little momentum spread. The recirculation therefore causes little variation in the injected full bunch length of ~10 psec. When reinjected into the module at zero crossing, the bunch, which is essentially long and with small momentum spread, is therefore slewed by the 27 MV module voltage to give a full relative momentum (energy) spread as follows.

$$\Delta p/p = 2\,(\Delta E_{linac}/E)\,\sin(2\pi(l_{bunch}/2)/\lambda_{RF}) \sim 2\pi\,(\Delta E_{linac}/E)\,l_{bunch}/\lambda_{RF}$$
$$\sim 2\pi\,(27\text{ MeV}/37\text{ MeV})\,(10\text{ psec}/667\text{ psec}) \sim 0.069$$

This is consistent with the observation described above. A more detailed treatment is provided by simulation [6], results of which are given in Figure 2 for the on-crest difference orbit diagnostic mode used to initially put 3 beams through the module.

In the simulation, the nominal lasing configuration as been modified as follows:

1. lasing is off,
2. module gang phase is zero (on crest), and
3. recirculator path length is adjusted to put 2nd pass beam back through recirculator at first pass energy of ~37 MeV.

The resulting beam exhibits a relative momentum spread

$$\Delta p/p = (38.6\text{ MeV} - 36.4\text{ MeV})/37.5\text{ MeV} \sim 6\%\,,$$

which is consistent with the preceding discussion.

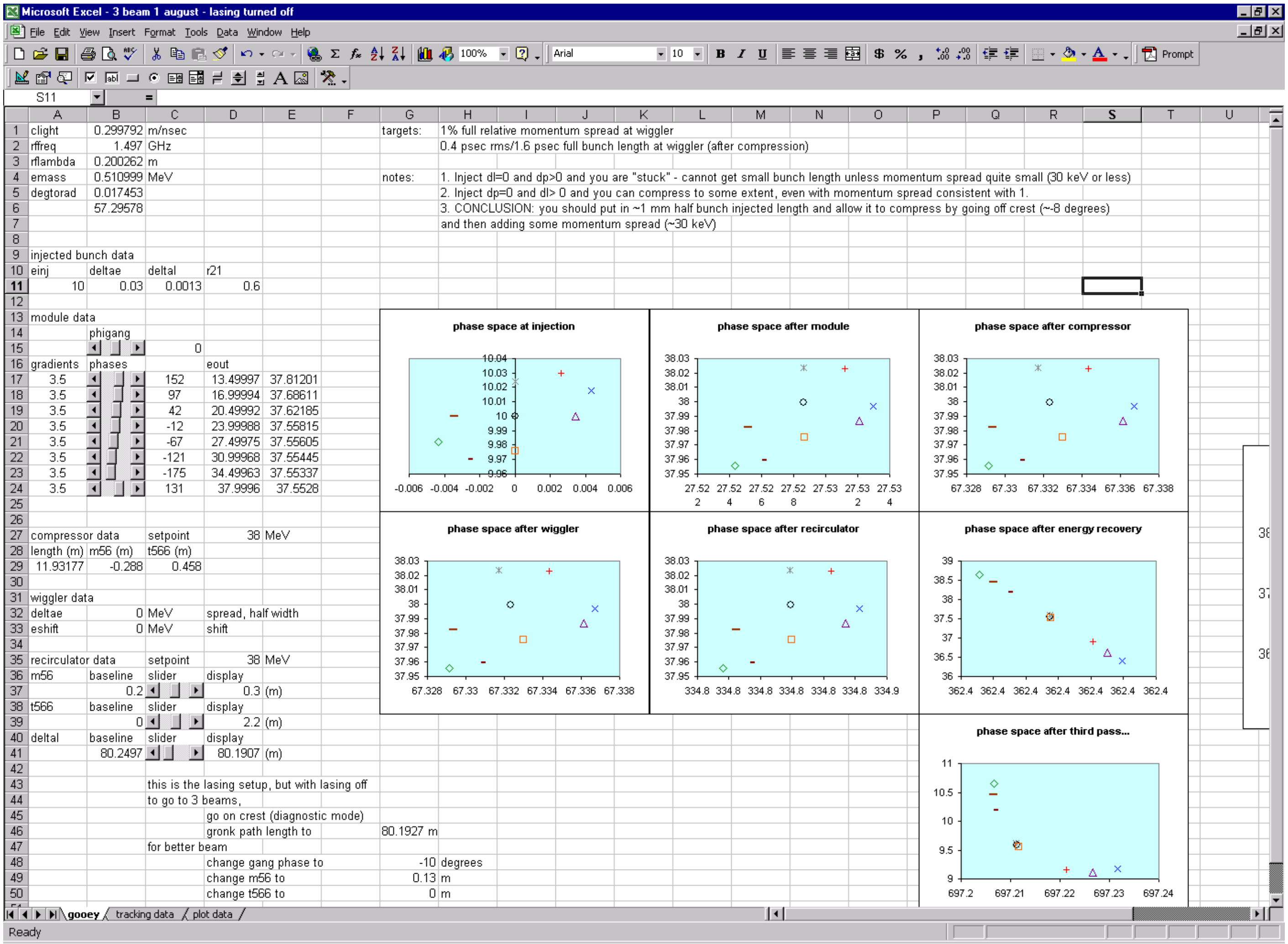

Figure 2: Simulation of initial 3-beam setup.

After the third pass through the module, the longitudinal phase space is quite distorted – the system is obviously not set for optimum performance – and the momentum spread is bad, consistent with the observed poor beam quality at the end of the machine.

Given the diagnosis of "bad beam because of bad momentum spread due to large overvoltage", a solution is clear. We need only set the driver up to compress the bunch length at reinjection! This is readily done by going back to the method like that used in the lasing setup, where we accelerate off (ahead of) crest and a use the (negative) momentum compaction (of the upstream chicane) to compress the bunch length at the wiggler. By accelerating off-crest and adjusting the recirculator global momentum compaction (away from the nominal lasing value, which explicitly does not compresses the bunch length at the front end of the module but rather introduces a phase/energy correlation intended to induce energy compression during energy recovery) we can similarly reduce the bunch length at reinjection, make the coasting beam short, and thereby minimize the second pass momentum spread. Moreover, there is an ancillary benefit. If we accelerate ahead of crest (as during lasing), the phase offset to zero crossing is a bit over a quarter RF wavelength. Energy recovery then will occur on the trailing edge of the trough ("two bits" over a half wavelength), and the overall momentum compaction (now negative, transporting a short bunch from linac back to linac, in contrast to the *positive* value transporting a short bunch from *wiggler* to linac used during lasing operation with energy recovery at the leading edge of the trough) will serve to provide some energy compression during energy recovery.

To check the efficacy of this concept, we arbitrarily chose a phase offset of -10^{o} (numerically, $+10^{o}$ on the EPICS RF controls). This particular choice was made because David had a senior moment, got confused, didn't think enough, and put in a rough value for phase, not the more precise $(-)7\text{-}8^{o}$ generally used during lasing. Results of simulation of this choice – with compactions adjusted to minimize the second pass momentum spread (and, as noted above, thereby providing some compression at the dump) – are given below in Figure 3.

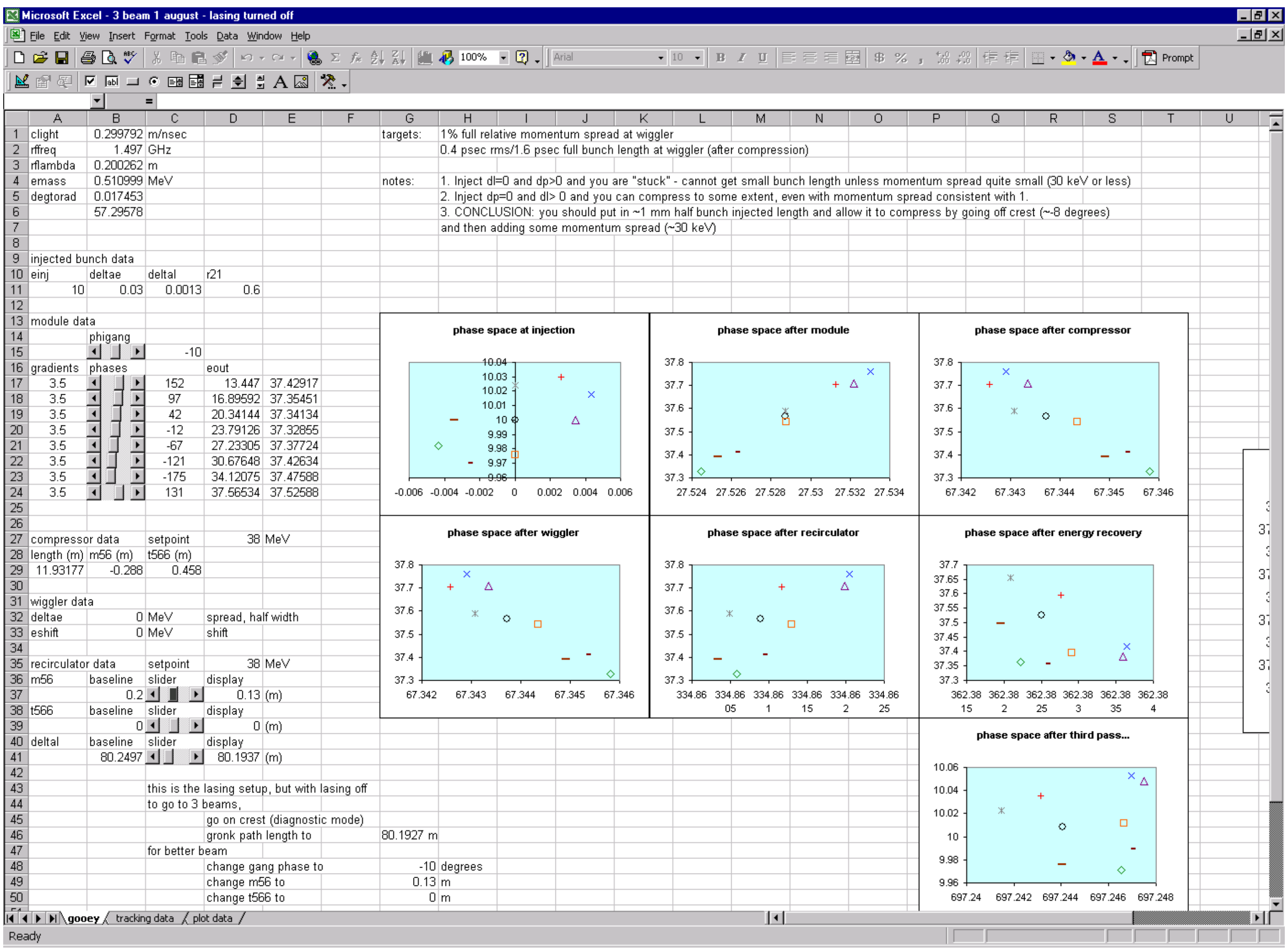

Figure 3: Simulation of 3-beam transport with compaction management at reinjection.

We note the second pass full bunch length at the front end of the module has been reduced – from ~10 psec at the start of the arc to about 2 psec at reinjection of the coasting beam. The second pass momentum spread has decreased from the 6-7% uncompensated value to only ~1%, just as on the first pass. When energy recovered, the additional energy compression provided by the negative module-to-module compaction (0.13 m from the wiggler-to-linac transport plus –0.288 m from the upstream optical chicane in the linac-to-wiggler transport) keeps the momentum spread at the 1% value through the energy recovery process. Both quad and sextupole trims were adjusted to achieve this simulated performance.

This operating scenario was implemented on 1 August 2001.

Observations on August 1st, 2001

On 1 August 2001, the module gang phase in the aforementioned 3-beam transport setup (allsave 672) was moved to 10^{o} off-crest ("+" on the accelerator, corresponding to "–" in the codes). The trim quads were adjusted to minimize the second pass momentum spread. Two beams were seen through the recirculator, and the third pass was acquired on ITV1G02, the energy recovery dump viewer. Some twiddling of the reinjection betatron match and the trim sextupoles improved beam quality a bit, and three reasonably well defined beams were observed on ITV1F02, at the end of the module. Figures 4 through 8 give viewer images from the final configuration (allsave 693)

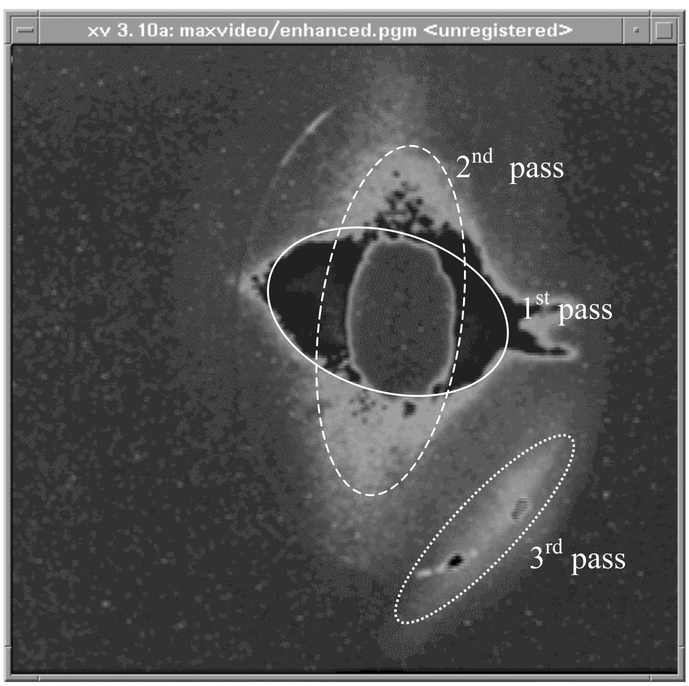

Figure 4: Viewer image at ITV1F02 with 3-beam transport

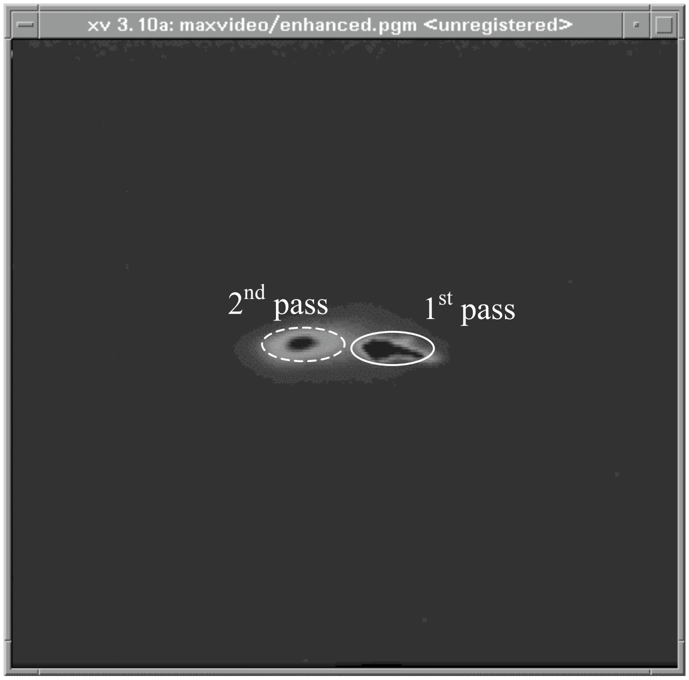

Figure 5: Viewer image at ITV2F00 showing first- and second-pass beams.

Figure 6a: Viewer image at ITV2F06, 1st pass beam only.

Figure 6b: Viewer image at ITV2F06, 1st and 2nd pass beam.

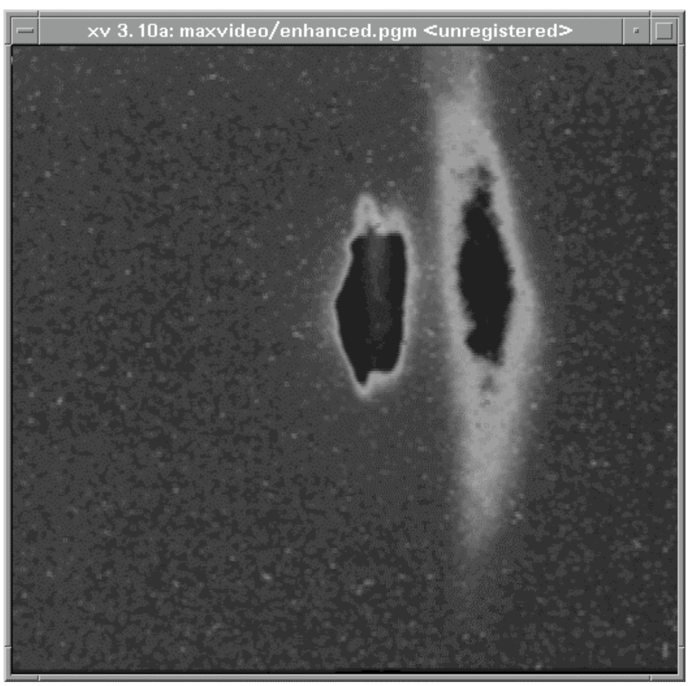

Figure 7: Viewer image at ITV4F05

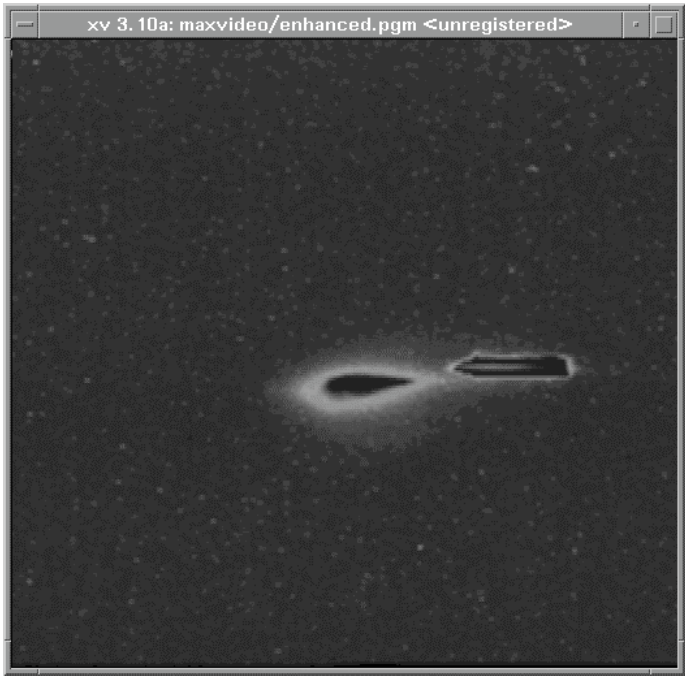

Figure 8: First and second pass beam at ITV2F06, early in the set-up process showing the two passes more distinctly than Figure 6b.

This configuration allows viewer limited operation but excessive beam loss at the module back end (1F02) and at the dump (1G region) precluded operation at higher beam powers. Simulation (Figure 9) suggests that further optimization is possible if we go to the nominal lasing setting of 7^o off-crest, make the wiggler-to-linac transport linearly isochronous, and adjust T_{566} using trim sextupoles. The energy spread simulated energy-recovered beam then decreases from the 100 keV value shown in Figure 3 to only 40 keV or so. Further adjustment of the reinjection betatron match may also prove useful. Should the beam quality improved further, CW operation at currents (in the module) as high as 15 mA could be achieved.

We remark that the RF system behaved quite well throughout this exercise. Despite the presence of beam near crest, on a zero crossing, and near trough (with, moreover, ~300 nsec lag between each phase during the start of the beam pulse), GASK values exhibited only modest initial transients (with amplitude of order ~10% or less of the nominal steady-state GASK value during the beam pulse), which settled out in ~50 μsec or so.

Fireworks for the 4^{th} of July

As an aside, on 3 July 2001 the authors and FEL personnel [7] investigated “what happens if we turn it all up?” While restoring the nominal 3 μm lasing configuration, a brief high-power test was conducted to verify that both machine acceptance and lasing performance were recovered. The accelerator ran CW, accelerating nearly 5 mA to about

48 MeV and energy recovering while lasing, yielding 1.48 kW upstairs at the end-of-line dump. Allowing for transport losses (~30%) and the modemaster pick-off (~6%) this translates to full output power of 1.48 kW/ 0.7 / 0.94 [8], or 2.25 kW. Some documentation is available at and around FLOG # 12832 (3 July 2001).

Acknowledgements

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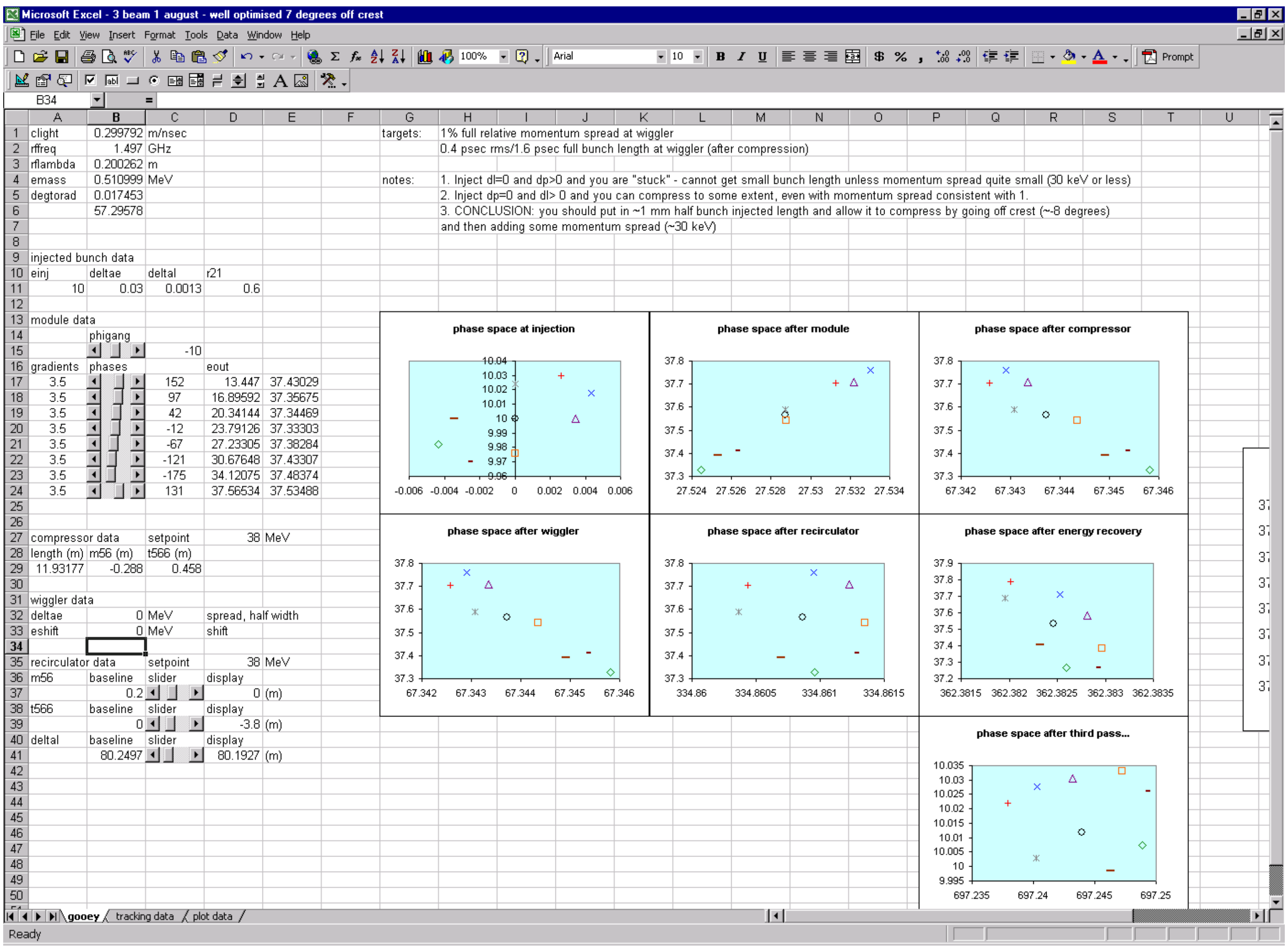

Figure 9: "Optimized" longitudinal match at 7° off crest, isochronous wiggler-to-linac transport, and adjusted T_{566}.

References

[1] J. Flanz and P. Sargent, “Tests With An Isochronous Recirculation System”, IEEE Trans. Nuc. Sci. pp. 3213-5, NS-32, 5, Oct. 1985.

[2] with J. Boyce, K. Jordan, M. Shinn, and R. Walker as co-conspirators…

[3] J. Flanz and P. Sargent, *op. cit.*

[4] A. Hutton, “Doubling the Intensity of an ERL Based Light Source”, to be published.

[5] J. Flanz and P. Sargent, *op. cit.*

[6] D. Douglas, “Modeling of Longitudinal Phase Space Dynamics In Energy-Recovering FEL Drivers”, JLAB-TN-99-002, 14 January 1999.

[7] Participants included J. Boyce, K. Jordan, M. Shinn, and R. Walker.

[8] M. Shinn, private communication.